A Review of Literature on Various Challenges and Opportunities of Quantum Computing

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Abstract

Quantum computing is reforming the way we address complex computational challenges by offering unparalleled speed and efficiency. Quantum computing is a technology that invokes the use of qubits instead of ordinary bits to solve computational problems, that would take supercomputers, millions of years to complete, in just a few minutes. Quantum computers use the idea of superposition to solve problems. The theory states that a qubit can either be in a state of 0 or 1 or both. While it increases the computational speed, quantum computing also comes with its set of implementation challenges because of its complexity. These challenges usually include security concerns, lack of standardization, quantum error correction, and software and algorithmic limitations among many others. Advancements have now been made for standardization efforts and quantum error corrections. The development of quantum cryptography has also laid the path for secure communications.

Keywords

Quantum computing, Noisy intermediate-scale quantum (NISQ) systems, Quantum Algorithms, Quantum error correction, Quantum Hardware and Quantum Simulations.

Introduction

The dawning of quantum computing in the field of technology marks the beginning of a revolutionary eon in information technology, leveraging principles of quantum mechanics viz. superposition and entanglement to solve classically intransigent problems. Current development especially in Noisy Intermediate Scale Quantum (NISQ) systems highlights both the immense potential and the technical challenges of quantum technologies. Topics like cryptographically discovered algorithms, quantum simulations, industry use cases in optimizations, machine learning, and material science quantum computing are set to reformulate computational limits across various sectors. Nonetheless, approving this approach requires going through significant obstacles such as error correction, scalability, and material challenges in hardware development. This review delves into the current scenario in quantum computing deriving acumen from emerging applications, hardware innovations, and inter-disciplinary research to draw a roadmap of the opportunities and limitations shaping the future of this department.

Literature review

In [1] the author examines the challenges and opportunities associated with near-term and noisy quantum computing applications, thus engaging with IMB's proposition to advance in accessibility and functionality. This paper highlights five key areas: (i) User-Friendly cloud access, (ii) The QISKIT Software Development Kit, (iii) Benchmarking through Quantum Volume, (iv) Error Mitigation techniques, and (v) Early quantum Applications like Quantum Machine Learning and Quantum Chemistry. The paper emphasizes IBM's commitment to the User-Centric Approach providing diverse access interfaces for Quantum Physicists, Scientists, and Developers, and supporting research through open access to Data and Metrics. This paper highlights the importance of hardware-aware compilations and optimization strategies that are tailored to noisy intermediate-scale Quantum (NISQ devices), which usually consist of tens to hundreds of qubits. To maximize hardware efficiency techniques such as approximate compilation and quantum volume are presented. Error mitigation methods usually include zero-noise extrapolation and probabilistic error cancellation extending computational reach until fault-tolerant quantum systems become feasible. This paper sifts through promising near-term applications like using quantum machine learning for evaluating complex feature maps and quantum chemistry for estimating ground-state energies with variational Quantum Eigen solvers. The author discusses IBM's use of Superconducting Transmon qubits along with hardware engineering challenges which also include microwave engineering and system reliability. Finally, the paper summarizes the potential of NISQ devices to drive innovation while also addressing the limitations of current quantum hardware.

According to Paper [2], the authors, post examination of the massive development that has come about Quantum Computing, suggest about its capacity for varied applications and constitutional principles that enable it. The Theory of Quantum Computing utilises the principles of Superposition and Entanglement to achieve computational goals that are not feasible for classical systems to perform. Alternatively, Qubits exist in multiple states at the same time, together, which in turn immensely enhances the computational power. The authors also shed light on the importance of Quantum Algorithms such as Shor's Algorithm, according to which there is a major challenge for today's cryptographic systems, and that is because of factorisation. A quadratic acceleration of search of unstructured data is permitted by some algorithms, here, for example, The

Grover's Algorithm. Apart from that, the authors have also looked into real-world applications like logistics, financial risk analysis, random number generation, satellite communications, etc. They assume that Quantum Algorithms possess huge potential for enhancement of performance in different domains. Techniques such as Adiabatic Quantum Computing, The Harrow-Hassidim-Lloyd (HHL) algorithm, and Quantum Annealing justify challenges like Constraint Satisfaction Problems, Linear System Solutions and Optimization Challenges. Quantum Simulators based on Richard Feynman's vision, grant researchers to understand complex quantum mechanical systems using tens of qubits therefore evading the extreme difficulty suffered by classical simulators. These techniques bring about improvements in operations like Quantum Magnetism and co-related electron systems. The challenges faced are noise, hardware reliability, algorithm development, etc are integral faltering points. Real-world issues of quantum systems are still coming up, with results expected in fields which require high computational power. Quantum Neural Networks and Hidden Quantum Markov Models (HQMMs) expand on the current efforts to exploit quantum mechanics for tasks like natural language processing and sequential data modelling. Conclusively, the paper illustrates the ground-breaking potential of quantum computing in ameliorating computation across scientific, industrial and technological domains.

In [3] the authors examine the operation of QUTAC, which stands for Quantum Technology and Applications Consortium. It is a German Consortium of ten major companies that range from industries like automotive, chemicals, pharmaceuticals, and insurance to technology. It aims to accelerate the industrialization of Quantum Computing (QC). The paper advocates for an application-centric approach, ranging from hardware-focused development to dealing with high-impact industry problems. QUTAC aims to guide technological progress and drive QC commercialization by creating industry reference problems and benchmarks. This process faces key challenges including proving QC's business value and integrating it into existing processes, establishing effective benchmarks, and fostering cross-industry collaboration to share expertise and de-risk investments.

The author describes how QUTAC emphasizes the relevance of application-specific benchmarks that extend beyond hardware metrics to assess QC performance meaningfully. Reference use cases are proposed as structured frameworks which include business value assessments, problem analysis, mathematical formulations, and verification routines to enable comparative evaluation of QC solutions. The consortium helps to identify significant challenges in quantifying QC's impact as a result of dependencies on technical and business factors. While applications like quantum-mechanical simulations have medium-term potential, applications like engineering simulations have longer-term prospects. To advance QC adoption the authors of this paper recommend prioritizing the development of industry-relevant benchmarks, demonstrating tangible business impacts, and fostering ecosystem-wide collaboration. They aim to deliver talent amplifications, education, and the making of industry benchmarks to ensure that QC solutions correlate with real-world problems. Despite the challenges suffered, the scope for metamorphic leverages in sectors like material science, logistics, and engineering accentuates the need for a unified and application-driven attitude toward QC industrialization.

According to paper [4], the authors shed light on the importance of material science in advanced quantum computing. It elaborated that material selection and optimization and critical elements for the improvement of solid-state qubits. The paper illustrates the influence of material science on various qubit platforms, namely superconducting circuits, quantum dot spins, colour centres, etc. Material Sciences have assisted in examining important metrics for assessing qubit performance, which includes coherence time, gate fidelity, gate duration, quantum error correction, etc. Apart from this, the authors also explain about the different physical platforms utilised in quantum computing, like superconducting qubits, which are based on Josephson Junctions for their non-linear elements. They come across various issues, such as defects and noise, which takes a toll on their performance. Challenges such as nuclear spin fluctuations and charge traps take place when the quantum dot bits, which rely on electron or hole spin states, are restricted within semiconductors. Colour centre qubits rely on impurities present in the host crystals. One such example is in the case of diamonds. They face problems such as paramagnetic impurities and surface issues. Trapped ion qubits are separated from noisy environments, which may be affected by material considerations face issues like electric field noise and drift. The paper also elucidates the protocol for the synthesis of each qubit type. The various qubit types that can be synthesised are E-BEAM lithography for superconducting qubits, reactive ion etching for quantum dots, chemical vapour deposition (CVD) for colour centres, CMOS/MEMS technique for ion traps, etc. They target the multi folding importance of hole spins in SI and GE quantum dots as an emerging venture for upgradation of coherence time and spin controls. Ultimately, the authors advocates that the revolution in all qubit platforms depends on the availability of high-purity materials and state-of-the-art processing protocols to enable the betterment of intermediate scale quantum systems.

According to paper [5], the authors have explored the prospect of quantum computing improving Machine Learning (ML) tasks by taking the help of near-term devices with hundred to thousand qubits. This advocates the need of enumerating stubborn ML challenges such as use of generative models in an unmoderated methodology of learning and the utilization of datasets with critical quantum-esque correlations. These areas grant quantum computers to equip meaningful insights by performing efficient, sampling complex probability distributions, representing data compactly and accurately, etc. The paper puts forward an argument that hybrid classical-quantum algorithms, in which quantum strengths deal with computationally comprehensive tasks within an ML pipeline, are crucial for leveraging the strengths of the ongoing quantum devices.

The paper elucidates certain challenges such as noise, limited connectivity, efficient data representation for quantum processors, etc, which implies solutions like "semantic binarization" and the Quantum-Assisted Helmholtz Machine (QAHM). QAHM puts together traditional deep learning, also known by, initial data processing, and quantum computing to model the most abstract data representations. When they are put together, it promises a more realistic path for surmounting the shortcomings of near-term quantum devices. The paper has provided a roadmap for identifying applications in quantum-assisted ML by detailing difficult ML tasks, hybrid solutions, and highly specialized datasets. This ground-breaking revolution goes beyond the limitations of conventional ML algorithms to attain the much sought-after quantum advantage.

The authors have suggested the result of specifying real-world datasets where quantum models have performed significantly better than the traditional classical models. This phenomenon is usually more common in sectors that are unrelated to Quantum Physics. Proclaiming quantum excellence in practical as well as real-world scenarios is a very critical step as it demonstrates the importance of Quantum-Assisted Machine Learning with near-term devices. They are upholders of inter-disciplinary participation as it helps in determining the high-value issues that meddle with quantum computing's capacities. Finally, the paper also sheds light on the utilization of the newest hybrid algorithms that can be integrated both effectively and seamlessly into both quantum and classical components. This ensures compatibility and efficient flow of information between the two systems.

According to paper [6], the authors have explored the groundbreaking possibilities and variety of use cases of quantum computing technology. Specifically in databases, at the same time detailing the various techniques, problems and algorithms. There have been many innovations in areas of supercomputing and trapped ion quantum computers. The systems run in the Noisy Intermediate-Scale quantum (NISQ) era. While they are powerful, they are extremely prone to errors. Here critical quantum computing concepts such as qubits, superposition and quantum gates are elaborated with specific importance to paradigms like Quantum Annealing and Grover's Algorithm, the latter providing a noticeable speed-up in database searches and optimization.

The paper puts forward a fascinating opportunity for databases using quantum computing while including improved query optimization, database manipulation and data security through quantum cryptographic algorithms. Algorithms such as QAOA and VQA are utilized for optimization. On the other hand, quantum-based security protocols like QKD and Quantum Private Queries provide protection at the advanced level. These days hybrid traditional quantum techniques are also coming forward to deal with issues caused by a limited number of qubits and noise, therefore quantum-based approaches act only as a temporary solution to help in the betterment of classical systems for resource allocation, keyword searches, and retrieval of information.

Conclusively, the authors have suggested various ingenious designs for quantum databases along with quantum vectors and distributed graph databases, which provide better efficiency, data security, and scalability.

In [7] the authors analyze the capabilities of quantum computing systems in finding the solution to complex optimization problems for energy systems. As the energy demand grows and renewable resources unify traditional optimization problems have started to cease due to the computational complexity of problems like facility location allocation, unit commitment, and heat exchanger network synthesis. To solve these issues, quantum computing uses phenomena like superposition and entanglement which essentially offers a different and more efficient approach for solution spaces. This paper features quantum annealers and gate-model quantum computers, particularly for optimization tasks. Limitations of hardware give rise to the need for hybrid classical-quantum approaches.

Despite all the possible advancements, quantum computing is still an emerging field. It often faces problems of limited scalability, precision issues, and error susceptibility which curbs its immediate application, compared to classical computational systems with are optimized for current hardware systems. This paper draws attention to the relevance of hybrid methodologies which bridge the gap between quantum and classical systems and lead the way for dynamic and real-time optimization in energy systems.

In [8] the authors of the paper probe into the evolution of quantum computing and its potential in the automobile industry, whilst also addressing challenges, product development, and Industry 4.0 applications. Factors like integration of disciplines, extensive software in vehicles, and the gradual advancement toward electric vehicles give rise to challenges such as the growth of complexity in automotive designs, manufacturing, and logistics. The authors suggest using existing problems as a framework to guide quantum computing development, identifying key applications in optimization, quantum chemistry, numerical simulation, and machine learning. This paper raises two specific issues namely (i) robot path optimization, which is formulated as a Travelling Salesman Problem, and (ii) vehicle configuration optimization, which is modeled as a Boolean Satisfiability problem which when solved using quantum computing reduces computational time and ameliorates problem-solving capabilities.

While quantum computing enables theoretical spurs and advantages over scalability, its advancement in this sector in the present times is limited by hardware constraints. The authors have hence underlined the importance of hybrid-classical approaches. They also highlight the need for standardized benchmarks that are tailored to real-world approaches and cross-industry partnerships to expedite developments. Ultimately, by addressing real-world and industrial challenges, this paper creates a strategic insight for integrating quantum computing solutions into automotive operations, in combination with classical computing systems, thus implementing technology as a long-term enabler for innovation and efficiency in the quantum computing sector.

The authors of paper [9] explore the optimization-focused approach of Quantum Annealing via NASA's encounter with D-wave Quantum annealers. While still in its early stages, the one significant question that comes to everyone's mind is whether quantum computers can truly outperform classical computers. Because of inadequate analytical proof of superiority for many quantum computers, empirical testing is the bottom line to assess their capabilities. Quantum annealing functions by using quantum techniques like tunnelling as a bargaining chip to escape local minima in optimization issues. The process of embedding problems framed in the Quadratic Unconstrained Binary Optimization (QUBO) onto the hardware is rather critical due to the limitations of physical qubits and their connections to the architectures such as the D-wave's Chimera Graph.

Quantum Annealing can be applied in a variety of sectors namely Planning and Scheduling, Allocation of Resources, Fault Diagnostics and Machine Learning. An appropriate example of this is the testing of Quantum Annealers in the optimization of NP-Hard scheduling problems. It was observed that there was an improvement in logistics and air traffic control and provided better assistance in case of disaster recovery. Since then, quantum annealers have also been used to diagnose faulty electrical systems, where the arrangement of the qubits and the circuit's structure mirror each other. Furthermore, applications of Quantum annealing have also been seen in machine learning, especially while training the Boltzmann machines and graphical models. The advantage of using Quantum Annealers in training the Boltzmann machines and graphical models over traditional approaches like Markov Chain Monte Carlo is seen in the efficiency of sampling methods.

The physics that drives Quantum Annealing comprises of Hamiltonian evolution where each qubit starts in a superposition state and then gradually comes down to a lower energy state representing a solution. To reach our objective of quantum speed-up, the paper lists several bottlenecks such as phase transition and decoherence induced by noise which impacts the efficacy of the work. Some imperative processes for achieving quantum speed-ups include coherent-tunnelling and multi-qubits co-tunnelling. However, these processes too face challenges caused by hardware imperfections and thermal fluctuations, as hardware is dependent on superconducting qubits which with the help of Josephine Junctions facilitate quantum state controls. Various Qubit types, viz charge and flux qubits come with trade-offs in noise susceptibility. Dealing with inter-qubit coupling and mitigation of decoherence continues to be pivotal towards the advancements of quantum annealing technologies.

The authors of paper [10] delved deep into the rising complexity and volume of biological data. This massive explosion in biological data driven by improvements made in omics has also given rise to compelling computational challenges. Quantum computing has proved to be better at handling tasks like protein folding, and multi-scale modelling genome analysis which might often be challenging for classical computers. Even though quantum computing has shown monumental potential in areas of molecular modelling and genome assembly, its practicality remains stifled by hardware limitations such as limitations on the number of qubits and decoherence effects. With these challenges in mind, the paper suggests a hybrid classical-quantum approach. This approach aims to utilize the quantum accelerators for specific subroutines while entrusting classical computers with the overall problem-solving, thus offering the best feasible near-term solutions.

Theories of Quantum Computing that are mostly used in biology include Variational Quantum Eigen solver, more suitable for Noisy-Intermediate Scale Quantum (NISQ) machines, and Quantum Phase Estimation for Molecular Modelling. While exploring Quantum Annealing and quantum approximate Optimization algorithm (QAOA) for genome assembly, it is noticed that Grover’s algorithm allows a more promising speed-up for read alignment in genomics. Quantum computing’s capability to handle robust correlated multireference systems like the ones found in enzymatic reactions and photosynthesis is a huge benefit for Quantum Chemistry applications. Even with limited practicality, Quantum Algorithms have a rather heuristic approach and are limited only by quantum hardware availability.

Regardless of the challenges faced, quantum computing has shown enough promise in reforming computational biology, particularly in electron structure calculations, genomic data analysis and biomedical imagining. The paper proposes that while the practical use of quantum computing in real-world scenarios is yet not achievable, the hybrid classical-quantum approach may take us a step closer to its practical usage.

According to paper [11], the authors are of the belief that by exploiting the principles of quantum mechanics, namely superposition, interference and entanglement quantum computers can get an upper hand on classical computers to find solutions to problems in various sectors ranging from logistics and drug design to financial modelling and material science. While quantum technology still remains in the Noisy-Intermediate Scale Quantum (NISQ) stage and is dealing with challenges like qubit decoherence and error correction, Google has successfully showcased true quantum supremacy, thus creating a benchmark. The main target, however still remains the solving of real-world problems that are far beyond the capabilities of classical computers. Advancements in Quantum Key Distribution (QKD) and Psot-Quantum cryptography (PQC) systems have become an essential move, as quantum algorithms could easily break encryptions like RSA. Because of this, quantum algorithms like Shor's Algorithm for factoring integers and Grover's algorithm for database searching have more profound implications than before.

This paper also explores various applications of quantum computing in sectors ranging from cybersecurity and medical diagnosis to climate modelling. This further underscores the need for better quantum programming tools like QISKIT and Cirq. Qubit interconnection, infrastructure, energy consumption and even scalability continue to be major obstacles in the development of quantum computers. A few imminent trends are quantum-enhanced AI, the quantum internet and sustainable quantum development. Conclusively, according to Richard Feynman's envisions, nature is inherently quantum mechanics. Thus, only quantum computing can precisely replicate the quantum processes.

In paper [12], the authors discuss the obstacles faced to secure the delegated quantum computers. This additionally emphasises the fact that early quantum computers are more prone to be accessed remotely as servers, thus entailing protocols enabling the computation of encrypted data. This ensures the client has privacy while utilising the resources of the server. The authors have developed a quantum system parallel to a homomorphic encryption system. This new development allows for computations to be processed on encrypted qubits without the need for decryption. The encryption key used by the operators are Pauli X and Z operators which then also decrypts the result with the encryption key which remains unknown to the server. The main motive behind designing this protocol is to make it more efficient as compared to classical computers. The clients are recommended to prepare and send only a single qubit from a set of four possibilities while performing the least classical computations. Furthermore, the complexity is also reduced as no particular quantum computation occurs between the client and the server.

The paper also discussed how the protocol allows in the execution of the Clifford Gates namely X, Z, CNOT, Hadamard, and Phase on encrypted qubits without additional resources, whereas non-Clifford gates call for an auxiliary qubit and limited classical communication. The feasibility of the approach has been verified by showcasing high-gate fidelities for single-qubit operations, with the aid of linear optics. The protocol also lists security concerns such as potential vulnerabilities where encryption keys can be leaked during photon emissions. These risks can be mitigated using improved source and detector technologies. Rather than just offering computational security, this protocol offers a more scalable solution for suture quantum servers by ensuring information-theoretic. Ultimately, this method takes a monumental step towards quantum computing and security by minimizing resource overhead and guaranteeing s strong security solution.

According to paper [13] the authors after examining all possible quantum computing techniques that are based on the principles of quantum mechanics have determined that this technology will help enable computations that are far beyond the reach of traditional computing systems. Qubits that utilise the concepts of quantum mechanics like entanglement and superposition recognise multiple processing states occurring at the same time. Models like Quantum dot Cellular Automata (QCA) allow alternative computing architectures while performing operations on qubits using quantum gates. Different qubit technologies namely superconducting qubits, trapped ions, photonic qubits and topological qubits pose various benefits and hurdles. Various branches of quantum computing include gate-based, analog, measurement-based and quantum annealers which provide advanced processing speeds and miniaturization. Contrary to all the advantages seen, compelling challenges faced by quantum computing include qubit stabilization, error correction, scalability and hardware development. Benchmarking moments in performance analysis include metrics like gate fidelity, quantum volume and Circuit Layer Operations Per Second (CLOPS). Ultimately, to tackle environmental concerns due to energy consumption and e-waste production, quantum computing provides sustainable benefits such as power grids and advancing climate research.

The authors of paper [14] emphasise the immediate call for sustainability in the field of quantum computing, saying the environmental impacts of quantum computing should be premeditated rather than considered for later. The authors further discuss both the pros and cons of quantum computing, stating that while quantum computing provides us with great speed, high computational power and an assorted array of functionality, it also takes a huge toll on the environment. Critical environmental concerns like high energy consumption, rare resource utilization and electrical waste tend to get ignored while paving the way for greater accomplishments in the field of technology. The lack of standardised benchmarks to assess quantum computer's environmental impact becomes a major challenge. To address and further assess the impact caused by the quantum computing life cycle, i.e. starting from production to disposal, a Carbon aware Quantum Computing (CQC) framework is suggested. The aim of this framework is to calculate the total carbon footprint emitted by quantum computers. This is achieved by considering embodied carbon from hardware production and disposal, operational carbon from energy and water consumption and application-based neutralization of carbon which is nothing, but a contribution made by the quantum computers towards a sustainable environment and thus providing sustainable solutions. While platform fragmentation and the absence of universal performance benchmarks continue to remain a challenge, Life Cycle Analysis (LCA) factors are often used to quantify the aforementioned factors under a unified metric.

This paper also underlines how renewable energy may be a key factor in mitigating the carbon footprint and environmental damage caused by quantum computers. The authors aim to do this by strategically placing data centres in areas that are abundant in sustainable energy sources. In addition to this, the paper also divulges alternatives like green manufacturing, modular designs and recycling of rare earth metals to reduce embodied carbon. Carbon emissions could be substantially counterbalanced by driving quantum computers to its full probable capacity. This may include optimisation of Haber's process for fertilisers, advancements in drug discovery, modelling climate change and improving the efficiency of batteries.

Given the plethora of energy consumed by the ICT sector and the break-neck growth of e-waste, the authors of this paper advocate for a multi-disciplinary collaboration of researchers, educators, leaders of the industry and policymakers to endorse sustainable quantum computing.

The authors of paper [15] initially start the paper by discussing the basics of quantum computing and the principles of quantum mechanics like superposition and entanglement that enables it. The authors argue that while they do not expect quantum computers to replace traditional computers altogether, they believe that the introduction of quantum computers holds immense power and can help solve complex problems, especially in the field of finance. Even with rapid progress, quantum computing still remains in the early stages of development mainly because of the challenges posed by qubit stability and scalability. Quantum computing could also greatly benefit the financial sector by managing risks, optimising portfolios and faster settlement of payments along with macroeconomic modelling. Some experimental results have even showcased promising and exponential computational speed compared to classical or supercomputers. This will enable tasks like VaR calculations for 1-million asset portfolios that would, on an estimate take a classical computer several hours, to be done in 30 minutes using a quantum computer. However, the authors also believe that the advantages of quantum computing will only be seen in case of exceptionally large problems. The practicality of quantum computers still remains uncertain because of economic factors like higher cost.

Judging from the security point of view, quantum computers also pose a threat to modern cryptography. Encryption algorithms like RSA and ECC that are of utmost importance in the financial world can be easily cracked using Shor's algorithm run on quantum computers. This thus gives rise to vulnerabilities like Harvest Now, Decrypt Later (HNDL), where even if the attacker cannot decrypt the intercepted information now, they can store it and decrypt it later when quantum computers are more widely and easily available. This vulnerability calls for an equally essential prevention technique called Post Quantum Cryptography (PQC), the goal of which is to develop cryptographic algorithms for classical computers that are quantum-resistant. The paper also suggests that while Quantum Key Distribution (QKD) seems to provide secure communications theoretically, it suffers from scalability and cost-induced challenges. The Bank of International Settlements (BIS) Innovation Hub Eurosystem Centre, Bank of France and Deutsche Bundesbank aim to strengthen the financial framework by investing in Post Quantum Cryptography. The project that looks after this has been named Project Leap. In the end, the authors recommend central banks and financial institutions to ready themselves for quantum computing-induced exploits as being unprepared would lead to inevitable financial losses.

Initially, the author of paper [16] discusses the working of quantum computers and the quantum mechanics principles it is based on. Being an underlying technology for ICCT (Information, Communication and Computing Technology), quantum computing technology often crosses paths with other technologies like artificial intelligence, data analytics, cryptography and even in the communications network. Around the world, top countries like the U.S., China, Canada, and the EU are leading the race with a fair amount of contribution from countries like Australia, Japan, South Korea and Singapore. Advancements in quantum computing will also benefit multiple industries, namely healthcare, finance, manufacturing, logistics and even the environment as a whole. Quantum computing has also given rise to improved findings in drug discovery, risk management, climate modelling, and optimization of the supply chain. Despite the advances, qubit stability, scalability and error correction continue to have a deterrent effect on development.

Additionally, the paper underlines the impact quantum computing has on cryptographic algorithms, causing an alarm for security individuals. To prevent security incidents the development of Post Quantum Cryptography and its ability to run on classical computers has been initiated as they stand quantum resistant. Monumental development in the field of quantum networking, sensing and education have opened new doors for research opportunities. Scope for advanced robotics, optimised networks, secure communication and possibilities in AI acceleration can be seen when quantum technologies are inculcated into ICCT technologies and analysed using the ABCD framework. In spite of its promising future, developments in quantum computing often face many hindrances for reasons such as hardware limitations and environmental interferences. Hence, even though quantum computing shows a promising future and startups are emerging, large-scale practicality remains a goal for the distant future.

Conclusion

Taking everything into account, it is evident that the quantum computing technology is very close to reforming numerous fields, starting from cryptographic algorithms and machine learning to optimization and material discovery. Even though there has been a substantial amount of progress in Noisy Intermediate-Scale Quantum (NISQ) which unlocked compelling near-term opportunities, there have been challenges to fault-tolerant, large-scale quantum computing such as addressing noise and decoherence. Developing scalability and improving the quantum algorithms to make them more advantageous over classical systems also remains a practical challenge on a large scale because of the unavailability of compatible hardware. They can be easily overcome by forming collaborations within diverse industrial sectors, facilitating multidisciplinary research, and making developments in material science. Hybrid quantum-classical approaches have provided efficient solutions to many challenges, including hardware limitations. With the emerging and ongoing advancements in quantum technologies and their integration into industrial and scientific sectors while reformulating various computational paradigms, it also invokes innovations across disciplines hence paving the way for a quantum-enabled future.

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